Electrical Tracking Performance of LLDPE-Natural Rubber Blends by Employing Combination of Leakage Current Level and Rate of Carbon Track Propagation

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ABSTRACT

Electrical tracking develops from surface discharge activity associated with the flow of leakage current on insulator surface under wet and contaminated conditions. Arcs created from this surface discharge phenomenon burn the polymer insulator material and create carbonized tracks in the long run. This paper reports on electrical tracking performance through the observation of leakage current and carbon track development of blends of linear low-density polyethylene with natural rubber (LLDPE/NR) either filled with or without alumina trihydrate. An electrical tracking and erosion test using the inclined-plane tracking method is conducted to study the overall performance of surface tracking properties. The combined effect of leakage current level and carbon track propagation rate is used as a new technique for describing the level of electrical tracking performance based on the proposed normalized degradation index. Morphological analysis is also carried out to investigate the surface microstructure before and after the tracking test. The experimental results show that different material compositions affect the leakage current and carbon track development. In addition, the calculated normalized degradation index has shown some correlation with the degree of surface deterioration.

Index Terms — **Carbon track, leakage current, morphology, polymeric insulator, surface degradation.**

1 INTRODUCTION

COMPOUNDING of polyethylene (PE) and natural rubber (NR) without cross-linking produces another material that is a type of thermoplastic elastomer (TPE). Recently works have been carried out to investigate the performance of such blends that can benefit both consumers and industry [1-3]. It is believed that with proper formulation blends of these two polymers can provide low cost alternatives to presently used materials with superior performance. Ibrahim [4] has reported the combination of PE/NR as the most compatible mixes in comparison to other thermoplastic-NR mixes. With further comparison among the PE materials, he found that the linear low-density polyethylene (LLDPE) is most compatible to NR during the mixing process.

Despite the fact that the blends of PE/NR have good mechanical properties, a study of the electrical properties has not been widely done. Most of the electrical studies are only focused on determining the dielectric properties of PE/NR blends [5] or on PE/synthetic rubber blends [6]. In fact, the study of electrical properties of PE/NR blends, particularly under high voltage applications, has not yet been performed. The contribution of this work is based on the interest in finding a good formulation of LLDPE/NR compound for high voltage insulating applications.

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Polymeric insulators may suffer from environmental and electrical aging stresses in service that may cause their performance to deteriorate [7]. It is well known that tracking has been the most common cause of insulation failure. Tracking develops from surface electrical discharge caused by the flow of leakage current (LC) on the insulator surface under wet contaminated conditions [8]. This LC results in non-uniform heating of the electrolyte that eventually causes a dry band to form at the narrow section where the LC density is highest. The whole voltage across the insulator appears across the dry band and surface discharge occurs when the electrical stress reaches the air gap breakdown level [9]. Arcs created from this discharge phenomenon burn the insulator material and create carbonized tracks. The mode of degradation from the formation of a carbon track through progressive material weight loss is called surface tracking.

This paper reports on investigations of the electrical tracking performance of different formulations LLDPE/NR blends for high voltage insulating applications. The effects of accelerated aging from environmental and electrical stresses are studied by measuring the LC and the rate of carbon track propagation on the material surface. A morphological study is also conducted to inspect the microstructure of the material surface before and after the tracking test.

2 EXPERIMENTAL SET-UP AND TEST PROCEDURES

2.1 MATERIALS PREPARATION

The linear low-density polyethylene (LLDPE) used in this study was an injection molding grade with a specified melt flow index of 50g/10 min. This resin was originally in the form of extruded pellets supplied by Titan (M) Sdn Bhd. The natural rubber (NR) used was a viscosity-stabilized grade of Standard Malaysian Rubber (SMR-CV) obtained from the Research Rubber Institute of Malaysia (RRIM). The extending filler [7,10] used for improving the electrical tracking resistance of the blend was alumina trihydrate (ATH). This powder grade filler was produced by BDH Ltd Poole, England and supplied by Excelab Technology Sdn Bhd.

A study, investigating the electrical tracking performance of a proposed thermoplastic elastomer material, was conducted on different formulations of the virgin

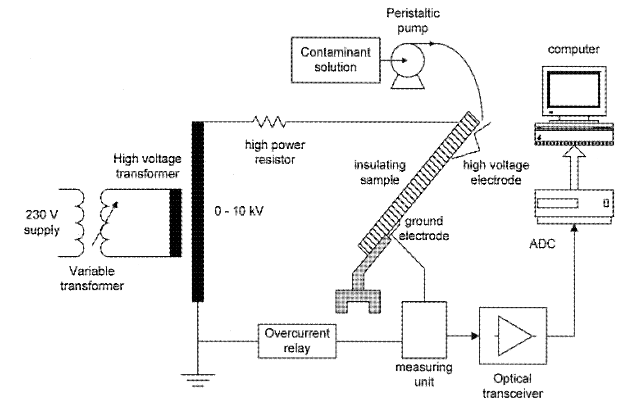


Figure 1. Experimental set-up for electrical tracking test.

compounds. Four groups of materials were prepared based on different weight ratios of the base polymer. Each group of polymer formulation contains a different level of ATH filler. Table 1 shows the compound formulations used throughout this study. The NR, which was received in a bale form, was first sliced into small pieces to facilitate easy loading into the mixer. All components were blended in a Brabender Plasti-Corder at 160° C with a rotor speed of 40 rpm for a duration of 13 minutes. Then the samples of each blend were compression moulded into slabs with dimensions of 120 x 50 x 6 mm^3 in an electrically heated hydraulic press at 160−170° C. The total moulding time was 15 minutes at a pressure of 100−120 kg/cm^2.

2.2 TRACKING TEST AND PROCEDURES

A tracking test was conducted based on the inclined-plane tracking method of IEC 587 [11], and the schematic diagram shown in Figure 1. The sample was mounted with the flat test surface on the underside, at an angle of 45° from the horizontal with the stainless steel electrodes 50 mm apart. A high voltage transformer rated 1.0 kVA, 0−10 kV was used to apply 2.5 kV across the sample. The sample was wet-contaminated with an electrolyte that contained 0.1% by mass of ammonium chloride with Triton X-100 non-ionic wetting agent. A peristaltic pump was used to continuously deliver the electrolyte at a fixed flow-rate of 0.15 ml/min. Eight layers of filter paper were used between the top electrode and the sample, which act as an electrolyte reservoir to ensure proper flow of electrolyte along the insulating material surface. The study of electrical tracking performance was carried out by mea-

Table 1. Compound formulations and coding.

Blend component	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4	D1	D2	D3	D4
LLDPE	20	20	20	20	40	40	40	40	60	60	60	60	80	80	80	80
NR	80	80	80	80	60	60	60	60	40	40	40	40	20	20	20	20
ATH*	0	50	100	150	0	50	100	150	0	50	100	150	0	50	100	150

*pph (part per hundred) of LLDPE/NR weight

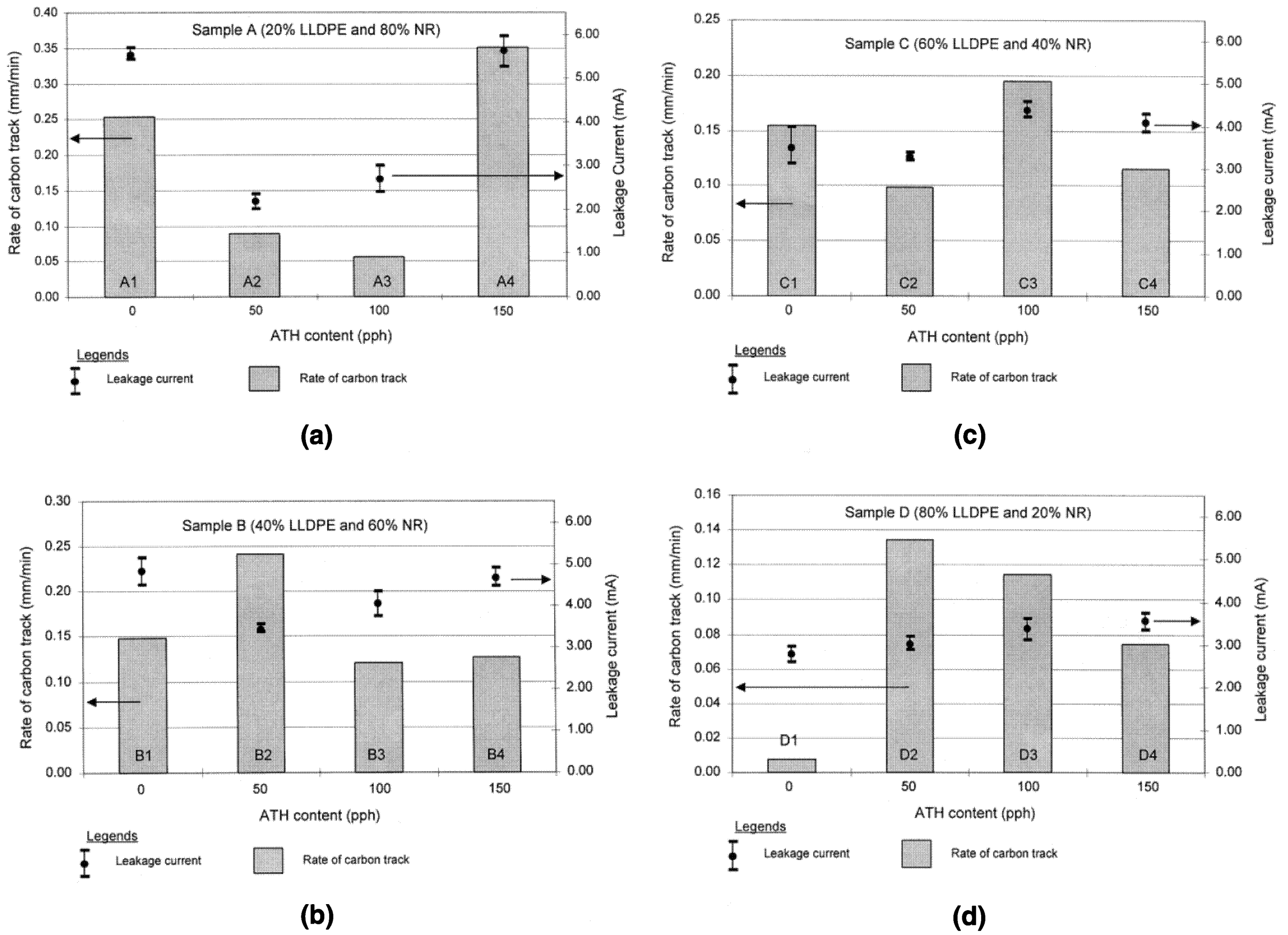


Figure 2. LC magnitude and rate of CT propagation of blends with different contents of ATH.

surement of surface LC and the length of carbon track (CT). An on-line LC monitoring system was developed to monitor the test every minute throughout the experiment. Five replicate measurements were made on each composition. The test was stopped after five hours or earlier if major erosion was observed on the material surface. At the end of the test, the range of LC, test duration and the length of CT were recorded for tracking performance analysis.

3 RESULTS AND DISCUSSION

3.1 RESISTANCE TO TRACKING AND EROSION PROPERTIES

Figure 2 shows the electrical tracking properties of different formulation LLDPE/NR compounds as well as the effect of ATH filler on tracking properties. Electrical tracking performance is determined from the LC level and the length of CT propagation on the material surface. The stress of LC tends to determine the onset of material degradation [12,13], which is related to the decrease of tracking resistance properties. In Figure 2, the range of LC is shown by the low and high bars along with the average value, which is represented by the black-dot. For all blend formulations, a range of 2-6 mA of LC is observed throughout the experiment. The same results are also found in the case of silicone rubber, polyolefin and polyethylene vinyl acetate [8,12]. The low level of measured LC exhibited by the blends of LLDPE/NR indicate a high surface resistance, and probably good hydrophobicity [14,15]. Based on the LC results, generally, the compounds filled with 50 parts of ATH per hundred parts weight of the compound (pph) have a characteristics LC suppression mechanism. It is believed that the ATH filler plays an important role in improving surface tracking performance by allowing an endothermic dehydration that decreases the amount of thermal decomposition products [15]. However, Figure 2d indicates an interesting result with the LC at its lowest value for the compound without ATH (compound D1). This result pattern that seems to be in contradiction with the other compounds is probably due to the higher content of LLDPE, which could impart high electrical tracking and fire retardance. It is believed that the LLDPE used in the blends might contain suitable fire retardance additive during manufacturing.

An investigation based on LC only will not give information on surface tracking performance. The propagation of CT has a significant influence in determining the capability of the material to withstand the electrical discharge activity [16]. The IEC 587 standard method proposes that the carbon tracking rate measurement be conducted as one of the favored criteria for determining the end point of the test. The CT propagation rate was determined in terms of the ratio of CT length to the test duration. The left Y-axis in Figure 2 indicates the rate of CT formation in mm/min. The data shows no correlation between the LC magnitude and the rate of CT. Some observations exhibit a high CT rate with low LC and vice versa. However, for compounds A (20% LLDPE and 80% NR) and C (60% LLDPE and 40% NR), both the LC value and CT rates are proportional to each other with increasing ATH filler.

To combine the LC level with the CT rate, the concept of conditional probability is applied based on a compound event [17]. This is done by calculating the normalized degradation index (*NDI*) for each sample. The value of LC and CT rate are normalized with respect to assigned critical values, and the equation for determining *NDI* is defined as follows

$$\textit{Normalized Degradation Index } (NDI) = \frac{I_n}{I_c} \cdot \frac{C_n}{C_c} \quad (1)$$

where I_n and C_n are, respectively the average LC and the rate of CT for the sample. The symbols I_c and C_c represent the assigned critical values. These critical values are selected based on the fact that the sample probably has not experienced any major degradation, or in other words, the sample is considered as a pass in the tracking test. Taking the value of C_n is 0.07 mm/min [11] (The tracking rate of 0.07 mm/min when coupled with a criterion of failure of 25.4 mm track length in 6 h or less will produce failure in 6 h) and the respected I_c of each composition, the calculated normalized degradation indexes of the samples are shown in Figure 3.

A value of *NDI* below 1.0 indicates that the samples pass and have good electrical tracking performance. Figure 3 shows that sample D1 (LLDPE/NR/ATH; 80:20:0 pph) is the best compound formulation for resistance to tracking and erosion because it has the lowest *NDI*. For the compounds filled with ATH, the A2 (LLDPE/NR/ATH; 20:80:50 pph) and A3 (LLDPE/NR/ATH; 20:80:100 pph) compounds offer good tracking resistant properties.

3.2 MORPHOLOGICAL ANALYSIS

A morphological study on the surface microstructure of the compounds was carried out using a scanning electron microscope (SEM) before and after the tracking test. Surface micrographs of compound D (80% LLDPE and 20% NR) will be discussed to illustrate compatibility of the blends under different levels of ATH content and the degradation caused by surface tracking. For the compounds filled with low and moderate content of ATH (50 and 100 pph), the basic components in the compound are homogeneously dispersed and only small agglomeration of the fillers occurs as shown in Figure 4a-ii and Figure 4a-iii. This shows that the interaction between fillers and the polymer matrix is strong. Reference [18] has reported a good blend of LLDPE/NR (70/30) where the rubber particles are dispersed in the continuous phase of thermoplastic components. However, for higher content of ATH fillers (Figure 4a-iv), the material surface becomes rougher due to difficulty in dispersing ATH uniformly in the compound. The particles of ATH filler appear on the surface. This roughened surface leads to an increase of LC as illustrated in Figure 2.

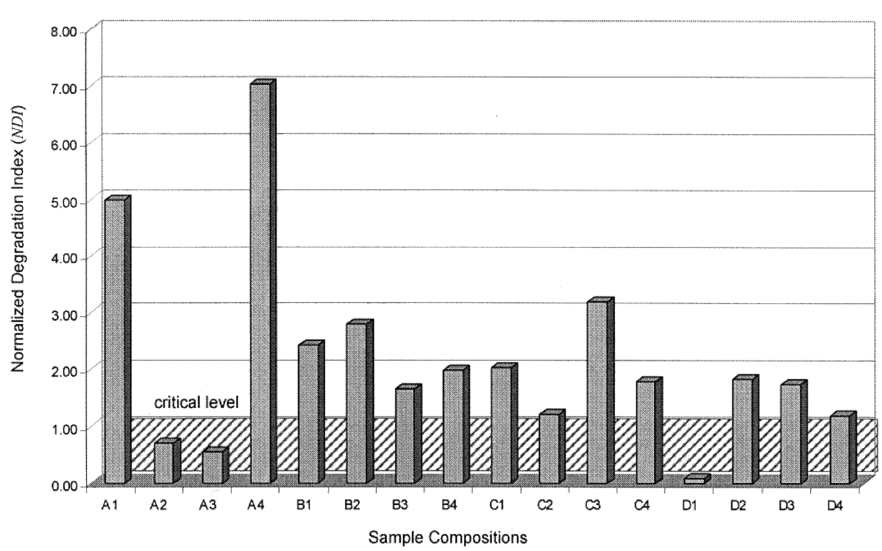
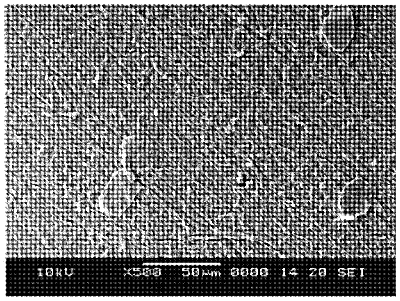


Figure 3. Normalized degradation index of all blend formulations.



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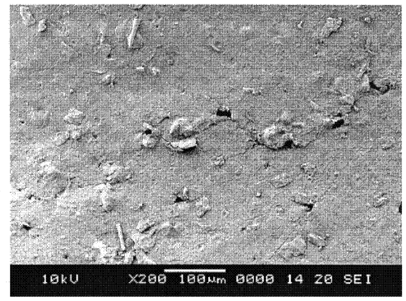

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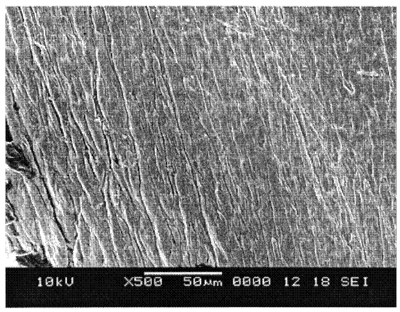

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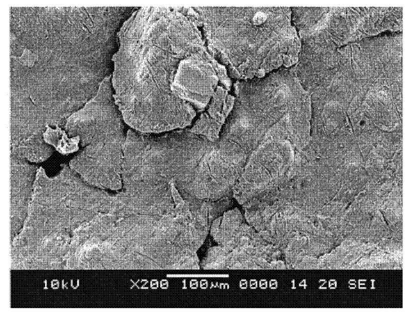

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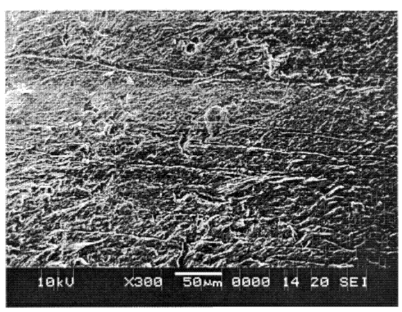

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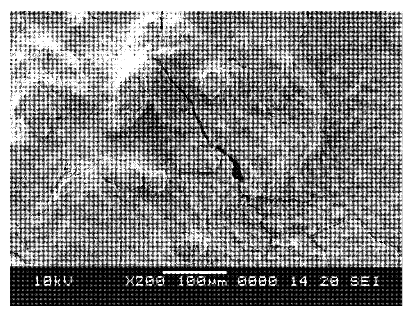

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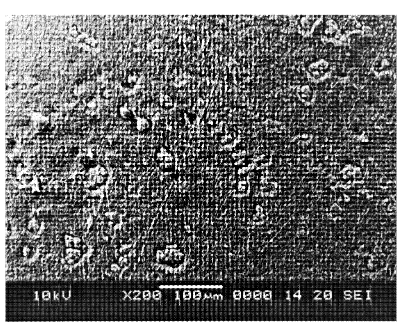

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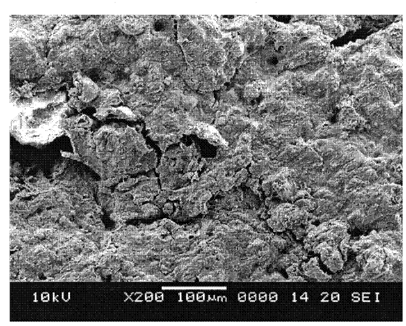

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Figure 4. SEM micrographs of samples D (80%LLDPE/20%NR) before and after the tracking. Test. 4a-i. Sample D1(0pph ATH) - before test; 4a-ii, Sample D2(50pph ATH) - before test; 4a-iii, Sample D3(100pph ATH) - before test; 4a-iv; Sample D4(150pph ATH) - before test; 4b-i, Sample D1(0pph ATH) - after test; 4b-ii, Sample D2(50pph ATH) - after test; 4b-iii, Sample D3(100pph ATH) - after test; 4b-iv, Sample D4(150pph ATH) - after test.

When the compounds are subjected to high voltage stress under wet contaminated conditions, the surface structure became damaged as a result of dry-band arcing. The surface structure became porous and cracks appeared as shown in Figures 4b-i, 4b-ii, 4b-iii and 4b-iv. The degree of surface damage depends on the level of LC as well as the electrical discharge characteristics [13,19]. Sample D1 (Figure 4b-i) shows minimum damage compared to the rest of the compounds. A little damage with less carbon residue was observed on the surface of sample

D1. This observation agrees with the lowest calculated NDI shown in Figure 3. In fact, physical inspection of the material surface shows that samples D2, D3 and D4 experienced major deterioration, while sample D1 shows minimum damage. The surface morphology of the samples, which is depicted in Figure 4, confirms the observation when major cracking was observed on sample D2, D3 and D4.

4 CONCLUSION

The electrical tracking performance and morphological properties of LLDPE-NR blends under environmental and electrical stresses are investigated by analyzing leakage current and carbon track development. Experimental results show that different compositions as well as the surface physical conditions affect the leakage current and discharges. Generally, the compounds filled with 50 pph ATH filler tend to suppress leakage current development. However, the compound of 80% LLDPE and 20% NR without ATH seems to be the best compound based on the least damage and the lowest normalized degradation index. By considering the effect of leakage current and carbon track development, the calculated normalized degradation index shows some correlation with the degree of surface deterioration. The index, therefore, provides more information in determining the electrical tracking performance of the polymeric materials evaluated.

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